

# USING THE VECTOR VORTEX CORONAGRAPH IN THE EXAO REGIME AT PALOMAR: LESSONS LEARNED

D. Mawet, R. Burruss, G. Serabyn,  
Jet Propulsion Lab - California Institute of Technology

5+ years effort:

B. Mennesson, S. Bikkannavar, J. Crepp, E. Bloemhof, P. Haguenaue, J. Hickey, J.  
Roberts, K. Rykoski, M. Troy, K. Wallace.

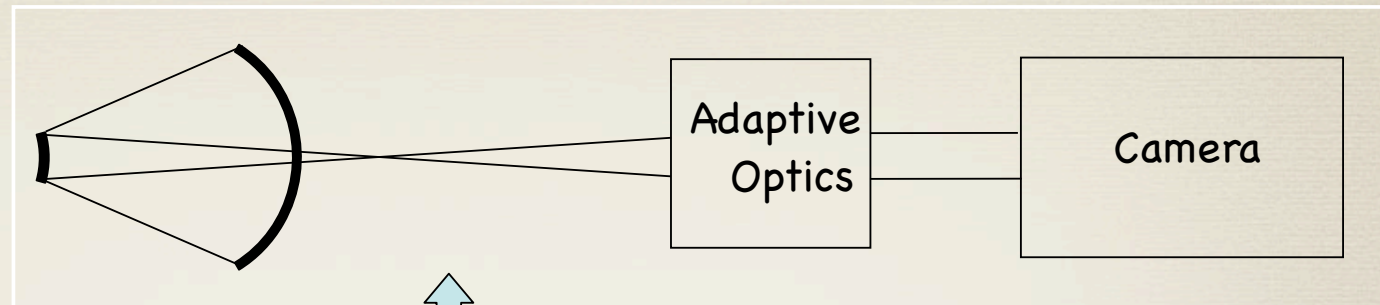
# Recipe for high contrast imaging from the ground

\* High Strehl Ratio => Extreme AO

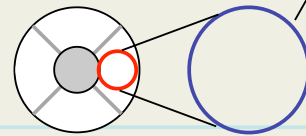


# Extreme AO

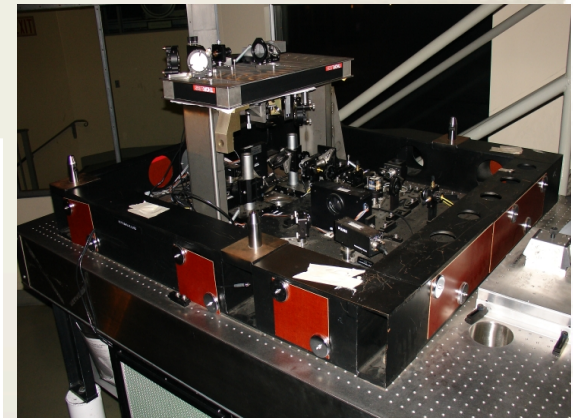
Existing  
Telescope  
Optics:



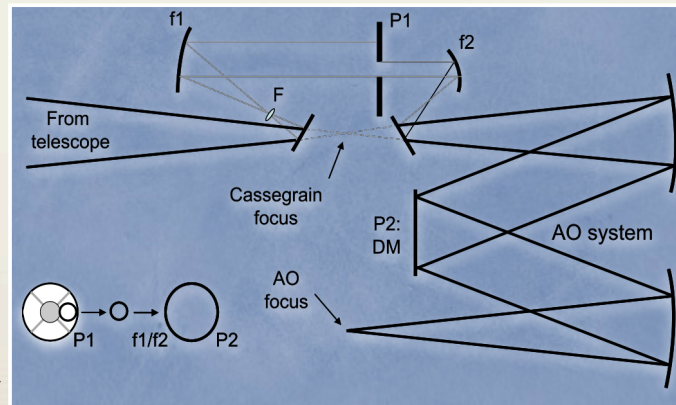
Subaperture  
reimager



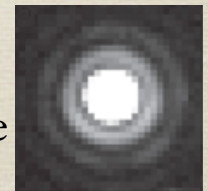
DM



- Keep pupil location at DM
- Magnify pupil (by  $f_1/f_2$ )
- Center sub-pupil on DM
- Maintain F# to AO system  
⇒ post-AO optics unchanged



Result: >90% SR, best image quality ever on a ground-based telescope



# Recipe for high contrast imaging from the ground

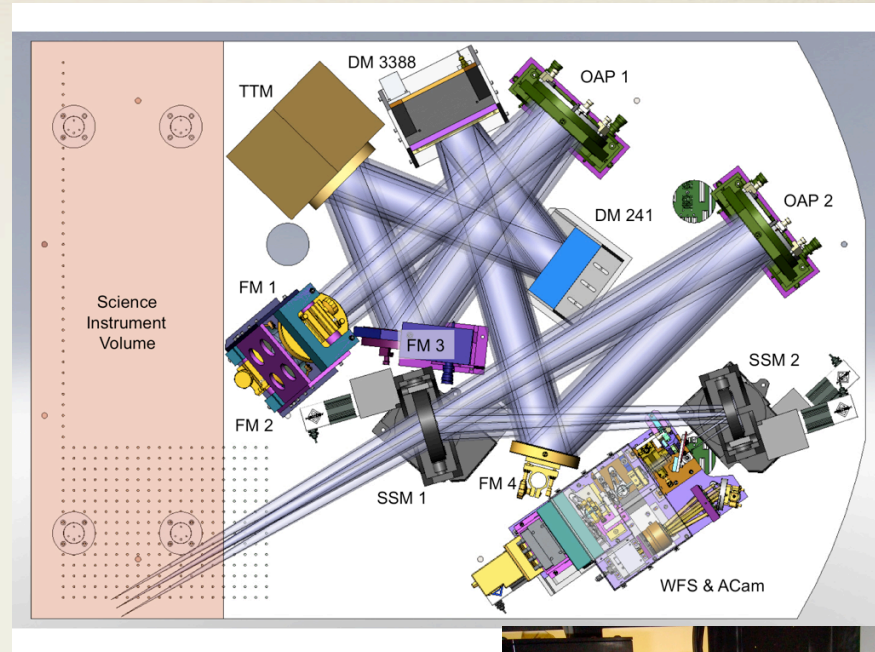
- \* High Strehl Ratio => Extreme AO ✓
- \* Pointing stabilization => new SSM



# New SSM

SSM are responsible for pointing accuracy and stability ( $\neq$  tip-tilt), which is the most fundamental requirement in high contrast imaging:

- Old SSM had 20 mas accuracy, and intrinsic drifts.
  - New SSM have *mas-level* pointing accuracy and very little drift.
  - Are now commanded with feedback from the science image.
- 
- *Dynamic tip-tilt is fundamentally limited by the tip-tilt mirror inertia, but can be specifically addressed by fine tuning the tip-tilt loop gain in real time.*



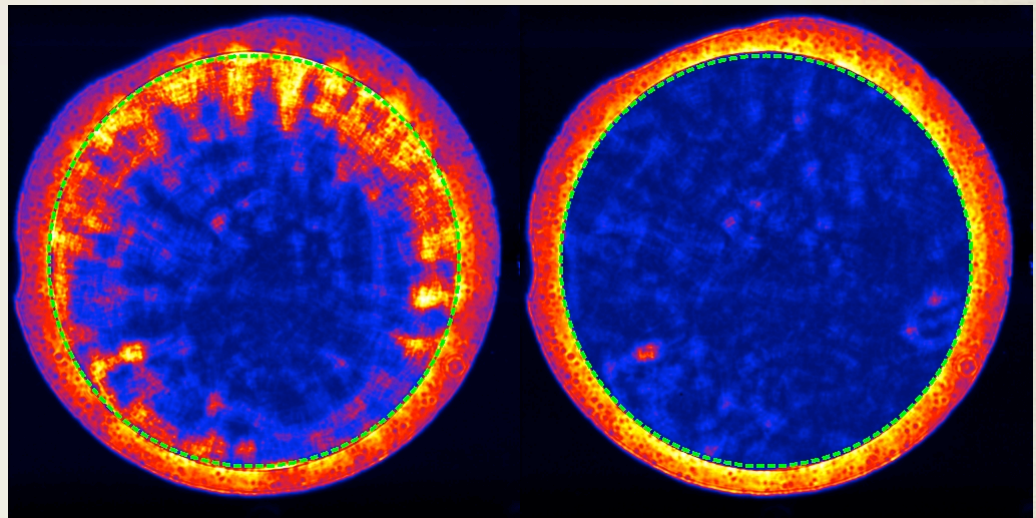
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- \* Low-order aberration (focus) => pupil imaging



# Fine focus tuning

Pupil imaging  
capability



No control loop correction, one time fine tuning.  
Then relying on AO to keep it steady

# Recipe for high contrast imaging from the ground

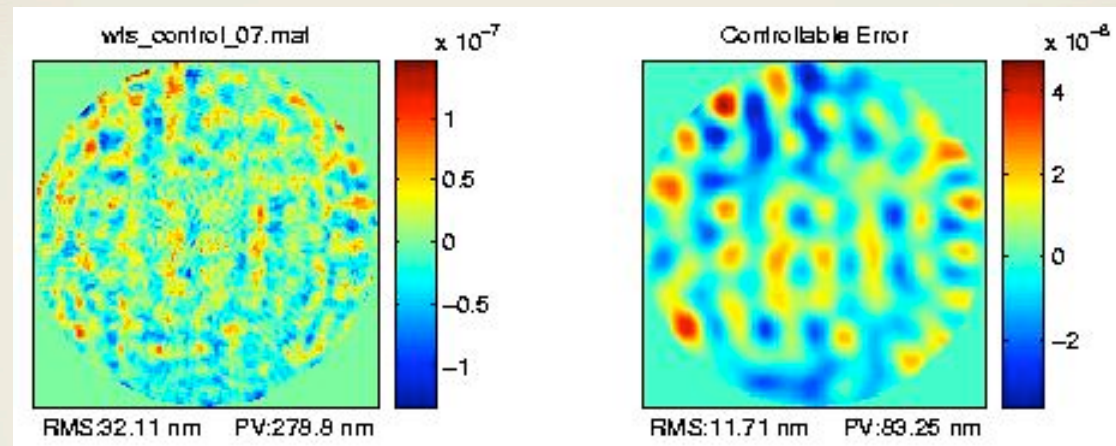
- \* High Strehl Ratio => Extreme AO ✓
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- \* Low-order aberration (focus) => pupil imaging ✓
- \* Quasi-static aberrations measurement and correction  
=> Modified Gerchberg Saxton phase-retrieval



# Autonomous Phase Retrieval Calibration

- \* Modified Gercherg-Saxton (MGS):
  - \* takes out-of-focus pairs of images with science camera (sense aberrations down to the final focal plane).
  - \* Off-line process (internal white light of the AO bench).
  - \* Performed for each new target.

# APRC

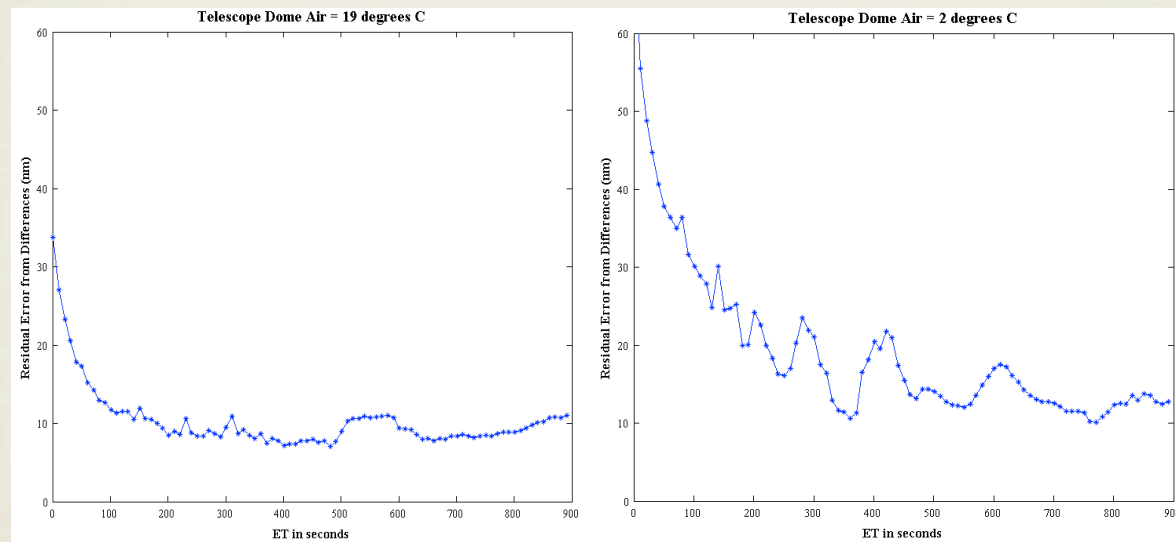


Best result: 11.71 nm rms within  
the DM bandwidth



# APRC limitation

\* Turbulence on the AO bench itself!



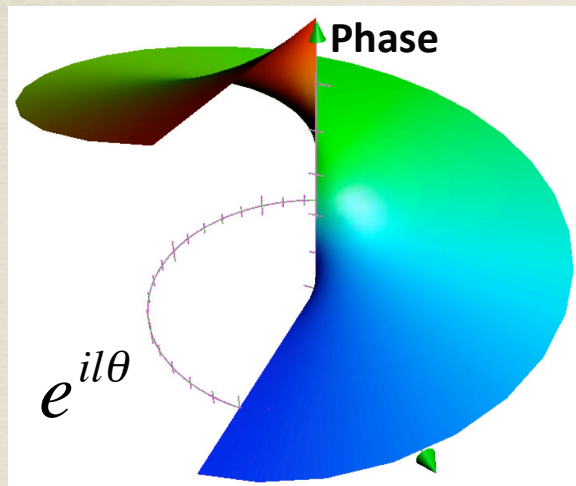
\* APRC only senses and correct phase aberrations...

# Recipe for high contrast imaging from the ground

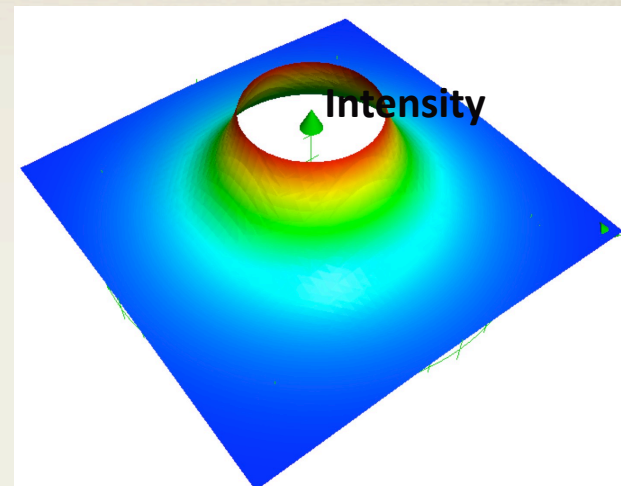
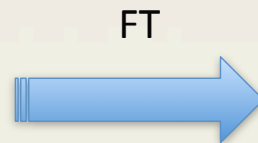
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- \* Small Inner Working Angle Coronagraph => Vector  
Vortex Coronagraph



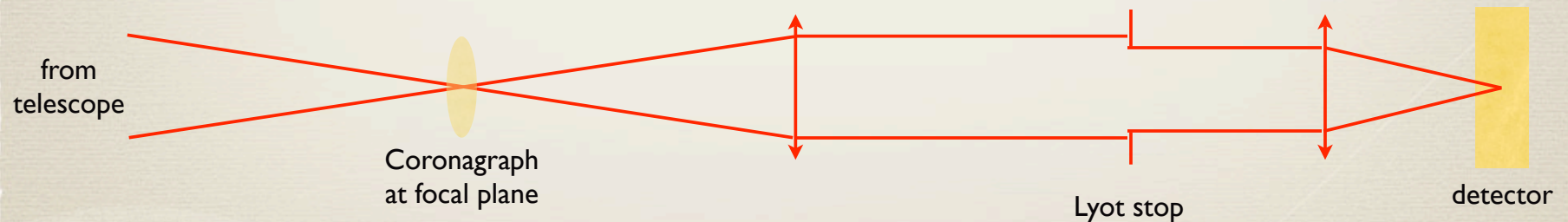
# Vector Vortex Coronagraph



"Phase screw dislocation" at focal plane  
 $l$  = topological charge



Clears out the relayed pupil



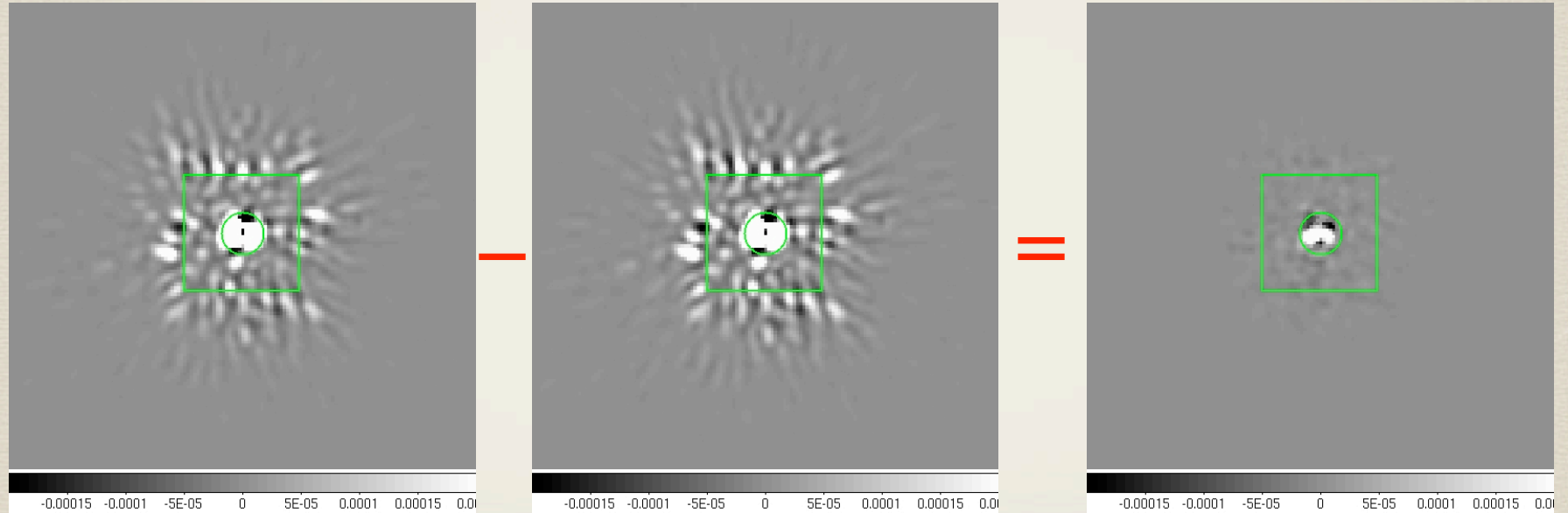
Selling points: small IWA ( $\sim 1 \lambda/d$ ), efficiency, clear  $360^\circ$  off-axis discovery space, rapid implementation

# Recipe for high contrast imaging from the ground

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- \* Small Inner Working Angle Coronagraph => Vector Vortex Coronagraph ✓
- \* Observing strategy oriented towards speckle calibration => RDI

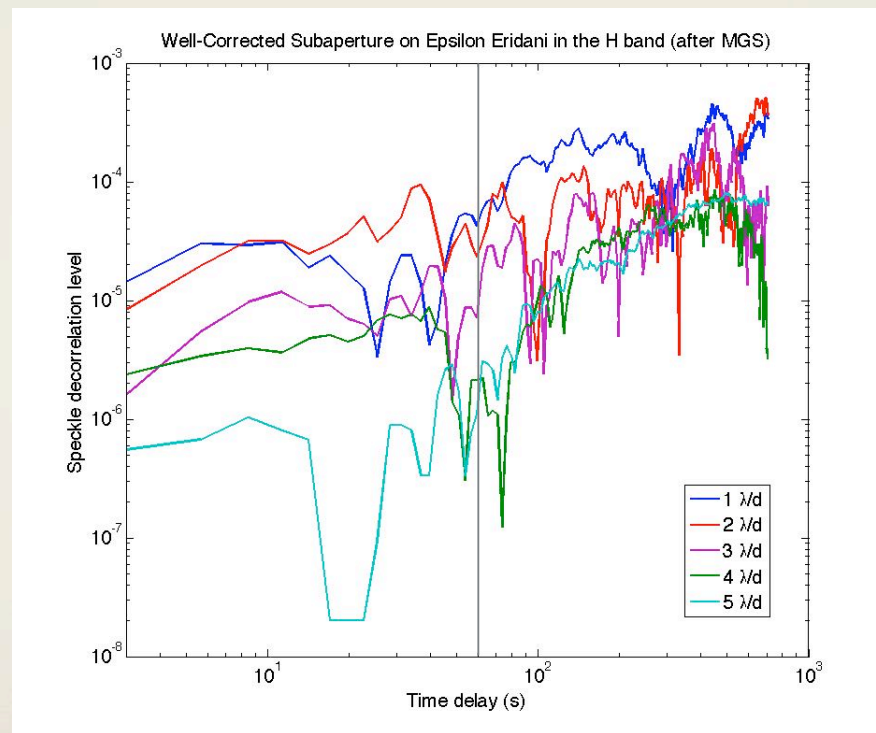


# The good ol' RDI with GOCI



# Observing strategy based on speckle decorrelation

1 ppm / min

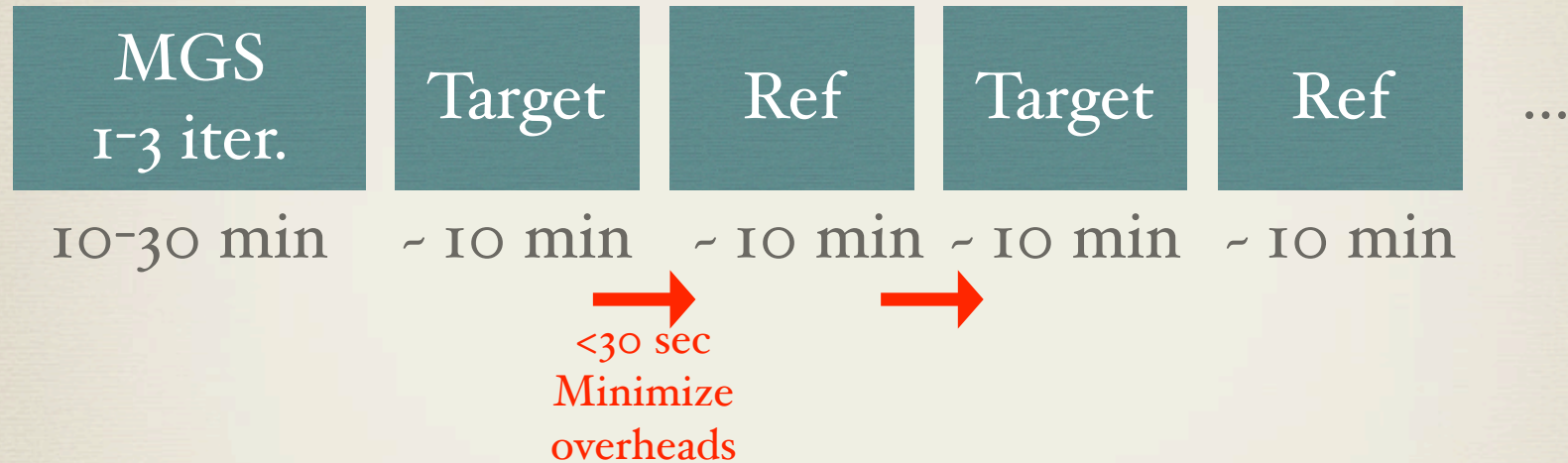


Extreme AO on sky data !



# Strategy - RDI

What is the best one can do without a CAL system and (quasi)simultaneous differential imaging?



Reference chosen with:

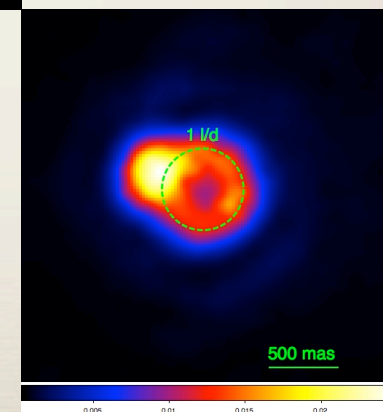
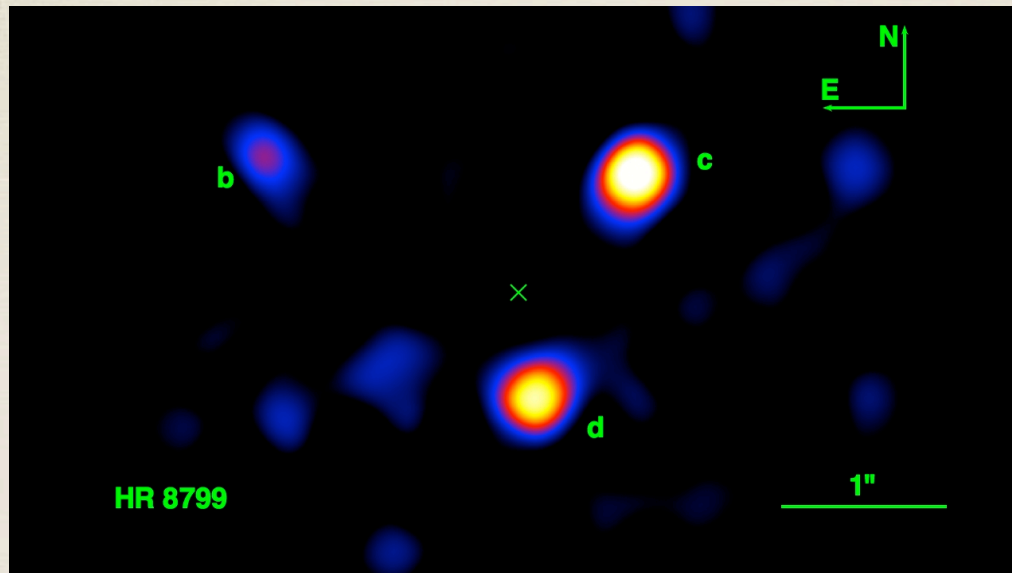
- same Vmag, K/H mag as the target.
- same dec,  $\Delta RA \sim 10$  min

# Recipe for high contrast imaging from the ground

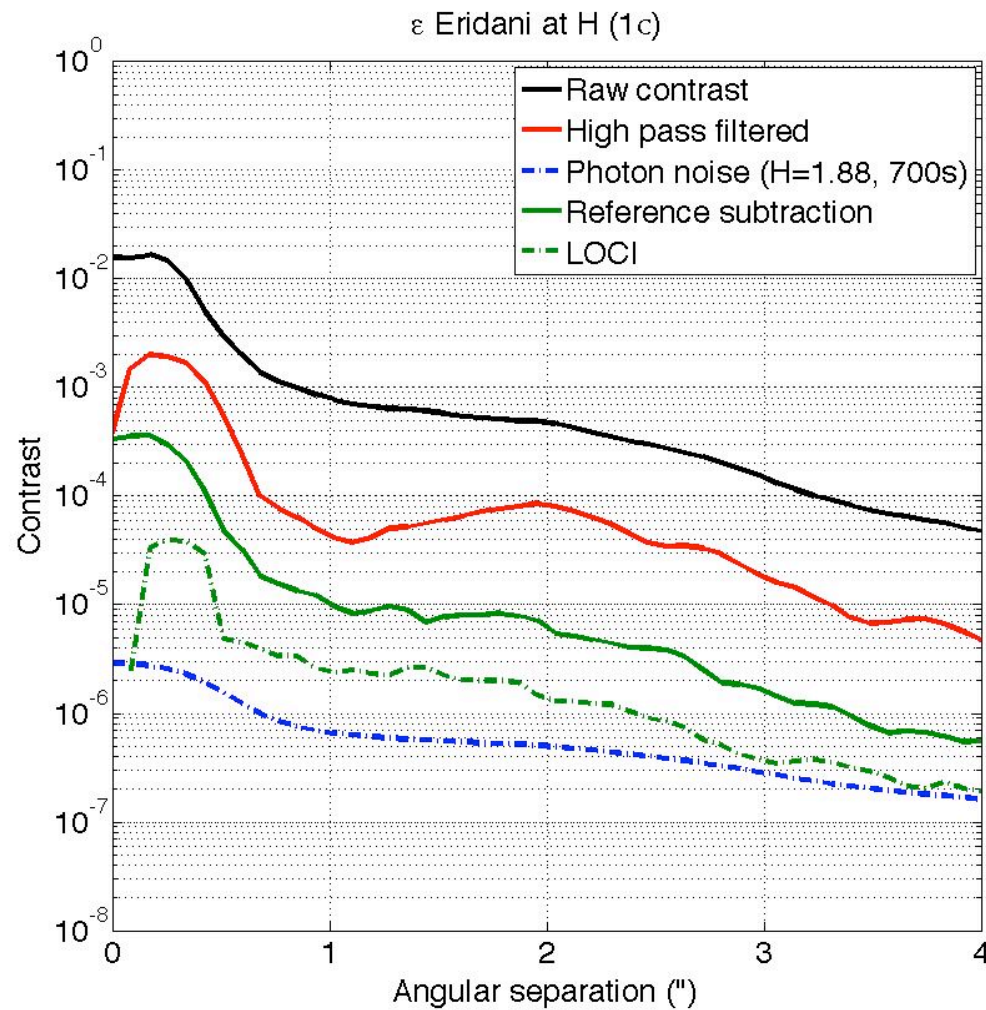
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- \* Smart data reduction method => GOCI & LOCI



# A few results



# Contrast analysis



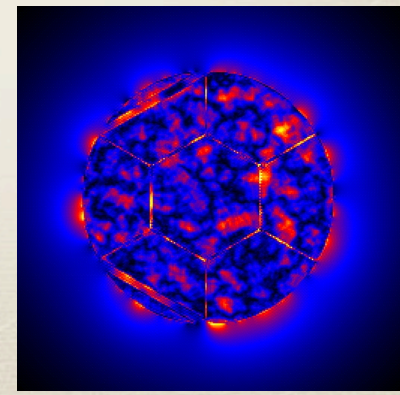
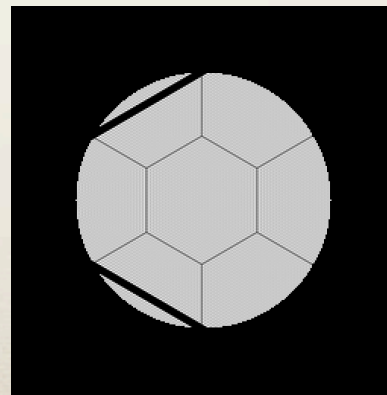
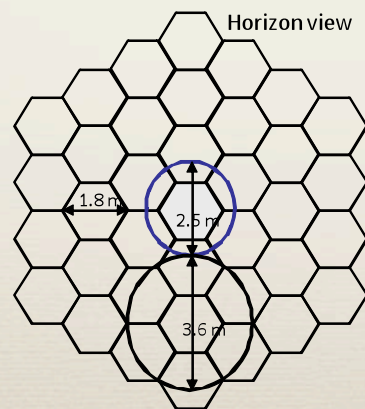
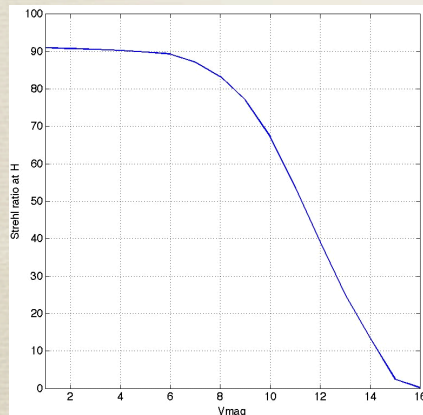


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# Future

- \* P<sub>3</sub>K - P<sub>1640</sub> - Pharo/Vortex: finest ExAO system in the world (64x64 DM for a 5 m aperture), only one in the Northern hemisphere, best correction and largest outer working angle !
- \* WCS at Keck (18 x 18 DM on a 3.6-meter off-axis portion of Keck)





# Wanna know more about the vortex ? Come see my posters !




## Vector Vector Vortex Coronagraph

for space-based and ground-based telescopes

**Dimitri Mawet, Gene Serabyn, John Trauger, Kurt Liewer, Dwight Moody, Rick Burruss, John Krist**  
Jet Propulsion Laboratory - California Institute of Technology

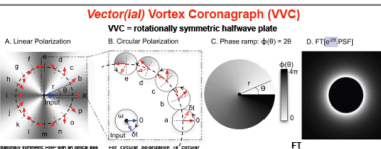
**Jeff Hickey**  
Palomar Observatory - California Institute of Technology

**David Shemo, Nada O'Brien**  
JDS Uniphase (former OCLI)



### Vector(al) Vortex Coronagraph (VVC)

VVC = rotationally symmetric halfwave plate



**Current device highlights**

- Central obscuration zone (CZ) radius: 1.5 arcmin
- Central obscuration zone (CZ) radius: 1.5 arcmin
- Central obscuration zone (CZ) radius: 1.5 arcmin

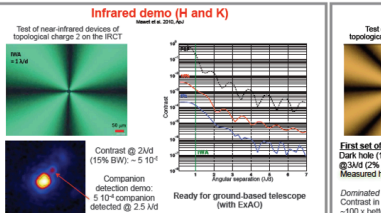
### Technical Breakthrough

Reducing the central obscuration (CZ) radius by a factor of 2

Current device highlights

- Central obscuration zone (CZ) radius: 1.5 arcmin
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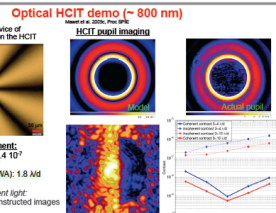
### Infrared demo (H and K)



Contrast @ 2λ (15% BW): ~ 10<sup>-4</sup>

Comparison detection demo: 5.10<sup>-4</sup> comparison detected @ 2.5 λ

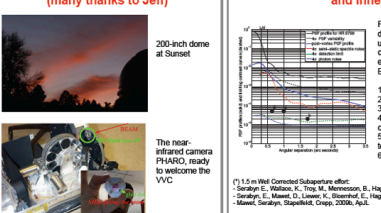
### Optical HCIT demo (~ 800 nm)



First set of measurement: Dark hole (10% BW): 2.4 10<sup>-4</sup> @ 3λ (2% BW): 2 10<sup>-4</sup>

Measured half-point (FWHM): 1.8 λ

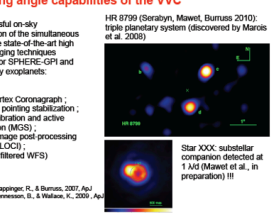
### Installation at Palomar (many thanks to Jeff)



200-inch dome at sunset

The near infrared camera PHARO, ready to welcome the VVC

### On-sky results, demonstration of contrast and inner working angle capabilities of the VVC



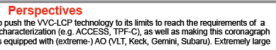
First successful on-sky demonstration of the simultaneous use of all the state-of-the-art high contrast imaging techniques envisioned for SPHERE-GPI and E-ELT to study exoplanets:


- 1- XAO (T)
- 2- Vector Vortex Coronagraph
- 3- max-level pointing stabilization
- 4- NCPA calibration and active compensation (MGS)
- 5- ultimate image post-processing techniques (LOCI)
- 6- (Spatially filtered FTS)

### Perspectives

Generation 2&3 under manufacturing: our goals are to push the VVC-LCP technology to its limits to reach the requirements of a space-based mission dedicated to planet finding and characterization (e.g. ACCESS, TPF-C), as well as making this coronagraph available for use at major ground-based observatories equipped with (extreme-) AO (VLT, Keck, Gemini, Subaru). Extremely large telescopes are also envisioned (EELT, TMT).

### Star XXX: substellar companion detected at 1 λ (Mawet et al., in preparation) II






## Enhancing the Vector Vector Vortex Coronagraph:

Achromatic design and chromatic filtering

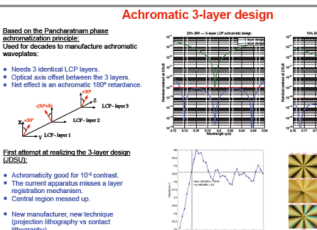
Mitigation of susceptibility to aberrations and stellar size

Immunitization to central obscuration, segment gaps and spiders

**Dimitri Mawet**  
Jet Propulsion Laboratory - California Institute of Technology



### Achromatic 3-layer design

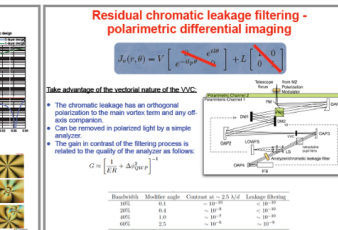


Based on the Pancharatnam phase information principle

Used for chromatic to manufacture achromatic waveplates

- Involves 3 identical LCP layers
- Optical axis offset between the 3 layers
- Half effect is an achromatic 180° retardance

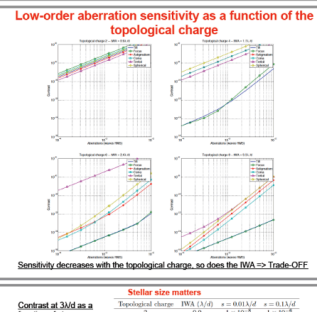
### Residual chromatic leakage filtering - polarimetric differential imaging



Take advantage of the vectorial nature of the VVC:

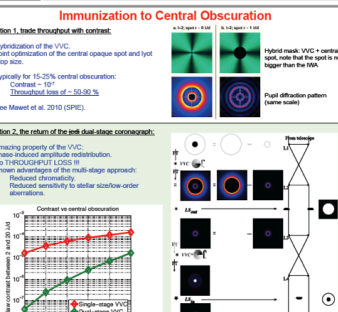
- The chromatic leakage has an orthogonal polarization to the main vortex beam and any off-axis companion
- Can be removed in polarized light by a simple analyzer
- The gain in contrast of the filtering process is related to the quality of the analyzer as follows:

### Low-order aberration sensitivity as a function of the topological charge



Sensitivity decreases with the topological charge, so does the IWA => Trade-Off

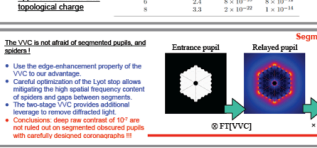
### Immunitization to Central Obscuration



Solution 1: trade throughput with contrast

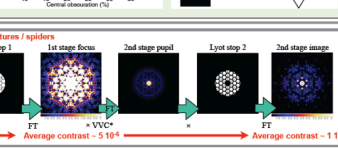
- Hybridization of the VVC
- Joint optimization of the central opaque spot and Lyot stop size
- Typically for 15-25% central obscuration: Contrast ~ 10<sup>-4</sup>
- Theoretical loss of ~ 50-90 %
- See Mawet et al. 2010 (SPIE)

### Stellar size matters



Contrast @ 3λ as a function of apparent diameter and topological charge

### Segmented apertures / spiders



The VVC is not afraid of segmented pupils and spiders

- Use the edge-enhancement property of the VVC to not advantage
- Central obscuration of the Lyot stop allows mitigating the high spatial frequency content of spiders and gaps between segments
- The two-stage VVC provides additional leverage to remove diffracted light
- Central obscuration size limited at 10° are not ruled out on segmented obscured pupils with carefully designed coronagraphs II

### Perspectives

The VVC coronagraph family provides a set of handles to mitigate chromaticity, sensitivity to low-order aberrations, stellar size, central obscuration, gaps between segments and spiders. A particular property of the VVC, called phase-induced amplitude redistribution can be used in a dual-stage layout to dramatically reduce the effect of central obscuration while maximizing the throughput, reduce chromaticity, stellar leakage and sensitivity to low-order aberrations. The results presented here and recent advances in wavefront control technology and post-processing techniques put phase-mask coronagraphs on the table again as potential solutions for extremely large and large ground-based telescopes.

### Star XXX: substellar companion detected at 1 λ (Mawet et al., in preparation) II

